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HIGH TEMPERATURES.

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TABLE OF CONTENTS

INVESTIGATION OF SHOCKS AT HIGH TEMPERATURES

SUMMARY

This investigation was conducted to verify and explain, if possible, the increase in total temperature found in shock diamonds as discovered by previous investigators.[1][2]

This report was limited to the burning of kerosene-air and hydrogen-air combustion mixtures, at pressure ratios from 1.6 to 3.0 and burner temperatures from 200°F to 1450°F. All total temperatures were recorded by chromel-alumel thermocouples; total and static pressures were measured by pitot and pitot-static tubes.

An increase in total temperature was found to exist in shock diamonds when burning a combustion mixture of kerosene and air. When a combustion mixture of hydrogen and air was burned, no increase in total temperature was detected. These results indicate that the afterburning of carbon monoxide is the most plausible explanation of the shock diamond phenomenon and that further investigation of this theory should definitely be conducted. Incomplete combustion and ionization are possible but not probable causes.

INVESTIGATION OF SHOCKS AT HIGH TEMPERATURES

INTRODUCTION

When a gas flows through an orifice or parallel-walled nozzle under a pressure ratio greater than that needed to produce sonic velocity, the sudden adjustment of the gas pressure to the lower back pressure produces a variety of angle shock patterns.[1] When these shock patterns or "diamonds" occur in high temperature products of combustion, it has been found, through the investigations of Bailey[1] and Bundy[2], that a definite total temperature rise occurs in the so-called shock diamonds. Bailey has reported excess temperatures in the first shock diamond of 200 to 300 degrees greater than burner temperature, burning a mixture of propane and air at a pressure ratio of 3.75. The report also indicated that the amount of excess temperature varied as the strength of the compression shock, but appeared to be independent of burner temperature. Essentially the same results were obtained for carbon monoxide-air and kerosene-air mixtures.

Bundy has reported total temperature increases in shock diamonds on the order of 150 degrees, burning alcohol and oxygen at a pressure ratio of 2.5 and burner temperature of 3000°K. However, he reported that exhaust gas temperatures have never exceeded burner temperatures. The temperature increase was calculated from observed temperature in the gas stream before and after shock.

The above investigations concerning this phenomenon are the only ones known to have been conducted to date.

The purpose of this report is to investigate the results found by Bailey and Bundy and if substantiated by experiment, to explain the phenomenon theoretically assisted by experimental results. This report will be limited to the temperature increases reported in shock diamonds.

This project was conducted during the period January to June 1948 at the Rensselaer Polytechnic Institute, Troy, New York.

EQUIPMENT

Equipment consisted essentially of the following:
2" diameter burner, burner extension, air metering device,
voltage regulator for spark ignition, fuel pump, fuel scale.
straight tube and U tube mercury manometers, thermocouples,
static and total pressure tubes, potentiometer, burner ex-
tension orifice caps and air compressor. A photograph of
assembled apparatus is shown on plates I and II. A schematic
sketch is shown on plate V.

Burner and burner liner are shown on plate III. The
burner, steel, 2" in diameter and 8" in length, had provisions
for spark plug installation and air and fuel supply as shown.
The burner liner (plate III) 1/32" inconel, was conical in
shape, perforated, and threaded at after end at which point
it was secured to the burner fuel nozzle tip. (plate III)

Burner extension (plate III and IV) consisted of a $6\frac{1}{2}$"
by 2" steel pipe, attached to the burner by a steel coupling.
The outer end was threaded to accommodate orifice caps. Thermo-
couple and pressure taps were provided as shown on plate III.
Overall length of burner and burner extension was 15",
measured from air inlet to orifice.

Air metering device was of conventional type, consisting
of a 3/4" metering nozzle. Voltage regulator for spark igni-
tion consisted of a powerstat, (type 116, PR1. V. 115, max.
output 7.5 A.) and an ignition transformer (type 638-171,
Jefferson Electric Co., Bellwood, Ill.) Fuel supply was com-
posed of fuel tank, and conventional centrifugal pump (max.

pressure 100 lbs. per sq. in.), driven by a 115 volt
General Electric Motor.   Fuel pressure (kerosene) was
measured by conventional bourdon gauge.   All of the above
parts are shown on plates I and II.

Various sizes of nozzle fuel tips were used of standard
commercial type.   In construction they were identical with
industrial tips, except for threading of the forward end to
receive the burner liner.   Sizes used were, .75, 1.00, 1.20,
1.50, 1.65 and 2.5, all gallons per hour.   While burning
hydrogen, a conventional gas burner tip was used, the latter
being supplied by industrial type hydrogen cylinder.   Fuel
tips of gas and liquid types are shown on plate III.

Straight tube mercury manometers (2) were of the con-
ventional type, capable of reading 60" Hg gage. Conventional
U tube mercury manometers were used, capable of 30" Hg
differential pressure.   All temperature measurements were made
with 1/8" unshielded, chromel-alumel thermocouples (plate III).
A Leeds and Northrup Potentiometer Indicator was used to re-
cord the thermocouple voltages.   Four burner extension orifice
caps were provided (plate IV).   They consisted of standard
2" brass pipe caps, each having a different size orifice.
Orifice sizes (diameter) were .4", .5", .6", and .7".   Outside
and inside surfaces were finished, the latter surface had a
11° taper toward the center.   Taper extended to within 1/8"
of orifice, the remaining 1/8" tip was 1/32" thick.

Total pressure was measured with a steel pitot tube
(plate IV), 3/4" in length, .100" outside diameter and .046"
inside diameter.   Static pressure was measured with a steel

pitot static tube (plate IV), $1\frac{1}{4}$" in length, .100" outside
diameter. Pressure tap, .040" in diameter, was located 3/4"
aft of leading edge. Air supply was obtained by a Schramm
Air Compressor, Model 210, rated capacity 206 cubic feet of
free air per minute, driven by a 50 H.P. Westinghouse Induc-
tion Motor.

Thermocouple and pressure tubes were held firmly in the
gas stream by a sliding plate arrangement which provided free-
dom of motion in three planes. Sliding plates were scribed
in .025" increments. This apparatus is shown on plate II.

Instrumentation location is shown on plate V. Static
pressure P_1 was measured by straight tube mercury manometer,
P_1^1 and P_2 were connected to U tube mercury manometer, as
were P_2^1 and P_3. P_4 and P_{o4}, pressures in the exhaust flow
were measured by a second straight tube mercury manometer.
T_{o2}, T_{o3} and T_{o4} were obtained by means of thermocouples.
Total and static pressure tubes were placed in the exhaust
gas stream in the same manner as shown for thermocouple.

Combustion mixtures consisted of kerosene-air and hy-
drogen-air.

PROCEDURE

Experimental runs were made using various pressure ratios, (P_3/P_a) and various burner temperatures (T_{o3}). Pressure (P_1) was varied to obtain desired P_3 and thus P_3/P_a. Fuel pressure was then varied until desired burner temperature (T_{o3}) existed. Actually since P_3 and T_{o3} are dependent on each other, it was necessary to vary both simultaneously to obtain desired conditions. Temperature traverses (T_{o4}), in long-itudinal plane only, were then taken each .100" measuring out from orifice. The position of the highest temperature in the gas stream did not correspond to the center of the orifice as had been expected. Thus it was first necessary to traverse the orifice area to determine position of greatest temperature and then traverse longitudinally. This position was checked each .50" and corrected if necessary. However, the variation over the 2.0" length traversed was slight. Total and static pressure traverses were made in the same manner.

In addition to varying the fuel and air pressure, it was necessary to vary the fuel nozzle tip size and the orifice size, in order to cover the range of burner temperatures and pressure ratios desired. A small amount of supply air was continuously bled off. This insured a steady air supply as then the compressor ran continuously. However, due to the combustion, fluxations existed in the air supply pressure (P_1) of $\nleqq 1/2$" Hg. Burner temperature was held constant insofar as possible. During some runs, the burner approached

instability resulting in burner temperature fluxuations.
However, during all runs, the variations were held within
the expected experimental accuracy.

Fuel pressure was varied from 30 lbs. per sq. in. to
100 lbs. per sq. in. Air pressure (P_1) was varied to give a
range of pressure ratios ($P\ 3/P_a$) from 3.0 to 1.6. The ex-
pected amount of difficulty was encountered in spark ignition
and maintenance of thermocouples. Due to prolonged operation
at high temperatures (1500° F) it was necessary to replace
two burner liners.

DISCUSSION

I. Possible Theories to Explain Total Temperature Increases
in Shock Diamonds.

A. Incomplete Burning

It is quite possible to account for increased
total temperature in a shock diamond if burning is
not complete in the burner. Unburned carbon would
combine with the oxygen in the exhaust gas stream
and produce additional heat. This burning of carbon
would be accentuated in regions of high pressure, e.g.
in the shock diamonds, causing the total temperature
to increase above that noted for regions of lower pressure.

However, all possible precautions were taken to
realize complete combustion. Different size burner
extensions were tested during which tests, cross sec-
tional temperature traverses of the burner proper and
burner extension were made. The length of the burner
extension was increased until maximum burner extension
temperature was lower than the maximum burner tempera-
ture. This was considered at least an indication of
complete burning. Throughout all runs, thermocouple
readings indicated a temperature drop in the burner
extension.

DISCUSSION (Continued)

Incomplete combustion, as defined in this report, means the combustion of the original hydrocarbons in the exhaust stream. No heat balance was attempted as the calculation of exact burner temperature was considered highly difficult, if not impossible. Assuming correct burner temperature, other variables involved make obtained results highly uncertain.

B. Ionization

It is possible that the violent deceleration of the hot gases in the shock could produce such a high concentration of ions that their bombardment and neutralization at the thermocouple metal surface could cause the metal to reach a very high temperature before energy equilibrium is reached.

The exact mechanism of the formation of ions due to this deceleration is vague and unknown. A possible explanation could involve the collision of the molecules at the shock front. That is, the high velocity molecules colliding with those molecules which have been greatly de-accelerated at the shock front. However, it is assumed that for collusion of molecules of comparable mass, there is a greater chance of the excitation of one of the molecules to an electronic state in which the nuclear separation is different from the initial value. This assumption seems to be justified experimentally by the spectrographic observation in flame sources of band systems which do not appear readily in other sources in which excitation is by electrical impact.[3]

The ionization potential of the molecules or atoms which can be identified in flame sources are known to be quite high, greater than 10 volts or 230 K cal.[20] Thus a large amount of energy is needed to produce ions. The most plausible source of ions is from C_2 and thus we may expect more ionization in fuels containing carbon. It

has also been found that a considerable fraction
of the kinetic energy of impacting ions is re-
tained after impact by the neutralized atom, the
remaining fraction of kinetic energy is delivered
to the thermocouple as heat. This latter fraction
is analogous to the accommodation co-efficient,
which is recognized in the impact of ordinary gas
molecules against a heated surface. For ions of
high molecular weight these co-efficients appear
to approach unity. Thus these results imply that
when ions bombard a thermocouple, mechanical mo-
mentum is imparted to the thermocouple to a much
larger extent than heretofor had been suspected.[7]
According to Compton, the following factors con-
tribute to the heating of a thermocouple in an
ionized gas: (1) the fraction of the incident
KE of the ion which is delivered to the electrode
(accommodation co-efficient) and (2) the true heat
of neutralization of the ion at the surface.

Thus there seems to be small doubt that if the
ions are present in sufficient numbers, a rise in
total temperature would result. However, at this
time experiment and theory appear to disfavor a
large concentration of ions. Although ionization
potentials are known for many substances, the cal-
culations of the deceleration in a shock front and
the resulting energy is most difficult to calculate.
This is due to the fact that the thickness of the

shock front, which would be the distance necessary
to compute the deceleration is most indefinite.
The measurement of the degree of ionization in the
gas stream would be a definite step forward in
determining the validity of this theory. However,
this measurement is not without many difficulties
and no indications have been found of experiments
along this line.

C. The lack of equipartition of energy:

Since it is definitely known that molecules possess varying degrees of translational, rotational and vibrational energy, it is entirely possible that these three forms of energy are not in equilibrium at all times. Thus, since temperature is only a measure of translational energy based on the Maxwellian theory of distribution, it is possible for a molecule to have more energy than temperature would indicate. Therefore, it is possible to think of the molecules as having higher vibrational and rotational energy than translational energy (not in equilibrium), as it leaves the orifice and then to have the shock equalize the energy distribution by converting some of the vibrational and rotational energy into translational energy, and thus increasing observed total temperature.

D. The Theory of Unstable Oxides of Nitrogen:

A possible explanation of temperature rise in shock diamonds is that some unstable oxides of nitrogen are formed in the region of shock due to the violent deceleration. This cause has been eliminated by Bailey.[1] He burned propane with pure oxygen and observed exactly the same phenomenon.

E. The After Burning of Carbon Monoxide:[3]

In the combustion of ordinary fuels containing hydrogen as well as carbon, it is generally agreed upon that the combustion of carbon monoxide occurs largely through the maintenance of the water gas

equilibrium. Also, there appears to exist a mechanism by which carbon monoxide and oxygen can react to form carbon dioxide. The exact form of this mechanism is doubtful, but experimental results have shown it to be quite possible.[26]

By use of spectro-analysis it has been found that the normal carbon monoxide molecule, which must be the final product of combustion regardless of the mechanism, is not built up from normal carbon monoxide and normal oxygen but from an excited state. Thus in the formation of carbon dioxide from the monoxide, an electronic transition must occur at some stage during the reaction. Since there is no spectroscopic evidence for the presence of electronically excited carbon monoxide molecules, it seems unlikely that the carbon monoxide molecules are first activated. Therefore, we are left to conclude that the carbon dioxide molecules are formed initially in a state which is not the normal electronic state of carbon dioxide. Thus the basic assumption of this theory is the fact that the carbon dioxide molecules are initially formed in an electronically excited state.

The electronic transition which must occur is therefore assumed to occur to this activated carbon dioxide molecule. The transition is from the excited state of carbon dioxide to the linear symmetrical ground state and is thought to occur either through collision or by radiation of the excess energy. In any case, the deactivation results in

the carbon dioxide molecule being in a state
of high vibrational excitation. (Franch-Condon
principle). This excess vibrational energy may
persist for as long as 10^{-4} seconds for pure dry
carbon monoxide, before equipartition with the
energy in the other degrees of freedom (heat energy).
In the presence of moisture or catalyst molecules,
the excess vibrational energy will mostly be lost
by collision and transferred into heat in a very
much shorter time. However, there is reason to be-
lieve that this temporary lack of equipartition of
the energy may lead to abnormally high dissociation
of the carbon dioxide molecules. There exists direct
experimental proof that abnormal dissociation in ex-
plosion flames of carbon monoxide burning in air does
occur.

It is the internal vibrational energy of the
molecules which governs the amount of dissociation
and thus, although the temperature of a gas as
normally recorded may be such as to expect a very
small amount of the dissociation of carbon dioxide,
the effective vibrational temperature may be very
much higher and the equilibrium value of the amount
of dissociation considerably greater. The carbon
dioxide molecules are believed to dissociate into
either oxygen atoms and carbon monoxide molecules
or into normal oxygen and excited carbon monoxide.
The recombination of the carbon monoxide and oxygen
result in after burning.

Thus after burning can be readily explained in terms of this abnormal dissociation, for although the life of the vibrationally activated molecules themselves is probably less than a second, the successive dissociation and recombination of the molecules will prolong the combustion process. The degree of after burning is directly affected by the pressure. More carbon monoxide and oxygen will combine in regions of high pressure due to the shift of the dissociation equilibrium.

It has been said that presence of a catalyst or moisture will deactivate the vibrationally excited carbon dioxide molecule more quickly due to collisions and therefore it is to be expected that abnormal dissociation will not be as great. Thus, for ordinary fuels, the after burning affect will be less than for pure carbon monoxide.

II.   Measurement of Flame Temperature.[3]

The measurement of the temperature of a flame
is one of the least satisfactory of physical measure-
ments. This is the result of the difficulty in de-
fining a temperature of a flame and also the fact that
there exist many experimental difficulties. In a
combustion process large amounts of energy are
released and this energy can take several forms. The
molecule may possess abnormal vibrational energy and
not be in equilibrium, therefore a measurement of the
translational energy would not be a true representation
of the energy of the molecule. Thus it is evident
that a flame temperature may have three possible
values corresponding to the effective rotational, vi-
brational and translational temperature of the mole-
cules. Since temperature is defined as the heat pro-
duced by the translational energy of the molecules,
assuming a Maxwellian distribution, it is evident that
temperature as measured may not be a true value.

Flames may contain many chemically reactive bodies
such as the radicals OH and CH, which may react with
any surface put in the flame such as a thermocouple,
liberate energy and raise the temperature of the
thermocouple above that of the flame. The recombina-
tion on the thermocouple surface of abnormally dis-
sociated molecules will also affect the observed
temperature.

The thermocouple loses heat by radiation, the correction for which is rather uncertain. It also loses heat by conduction into the cooler supporting leads, but this loss is so small in comparison to others that it may be neglected. In high velocity measurement corrections are required for the cooling affect.[1] This latter effect involves the fact that total temperature exists only at the nose of the thermocouple and the sides will come into equilibrium at a temperature above the static temperature. Thus the thermocouple will indicate a value less than true total temperature.

From the above, it is evident that, qualitatively, the values obtained by the use of thermocouples is indeed of doubtful reliability. Fortunately, however, this report is primarily concerned with temperature comparison rather than exact values. Although it is of importance to consider the thermocouple limitations when interpreting results, it is felt that thermocouples are sufficiently accurate to indicate temperature trends.

RESULTS

The following experimental runs are included in this report:

Fig. No.	Pressure Ratio (Po3/Pa)	Orifice	Fuel	Burner Temp. °F	Remarks
1 & 2	2.85	.6"	Kerosene	790	(1)
3	2.93	.4"	"	1002	(2)
4 & 5	2.93	.4"	"	1450	(3)
3	2.99	.4"	Hydrogen	990	(4)
4 & 6	2.99	.4"	"	1460	(5)
2A	1.64	.7"	Kerosene	790	(6)

(1) Total temperature, total pressure, and static pressure traverses made.
(2) Total temperature traverse only.
(3) Total temperature and static pressure traverse made.
(4) Total temperature traverse only.
(5) Total temperature and total pressure traverses made.
(6) Total temperature traverse only.

Figure (1) verifies previous reports as it is readily seen that when a gas flows through an orifice under a pressure ratio greater than that required to produce sonic velocity, the sudden adjustment of the gas pressure produces a variety of angle shock patterns. The pressure traverses also indicate that the first angle compression shock originates from the jet boundary. Figure (2) indicates that a total temperature rise occurs in the region of high pressure in back of the shock waves. Each "hump" in the temperature curve agrees exactly with the position of the shock diamond. This same result was observed for varying pressure ratios of 3.0 to 1.9 with burner temperatures of 200°F to 1450°F, using kerosene as fuel. Figure (2A) is the total temperature traverse at the same burner temperature as in figure (2) but at a pressure ratio of 1.64. The variations of total temperature are slight,

approaching the magnitude of potentiometer fluxuations.

The apparent rise in the total temperature curve as distance from orifice increases is due to two causes. First, the thermocouple was placed in the center of the orifice at zero position, which was later found not to be the hottest portion of the gas stream. Second, the traverse was not parallel to the stream. This combination resulted in the thermocouple reading lower than the maximum temperature at zero distance and reading higher temperatures as it traveled across the stream into regions of higher temperature as the traverse progressed.

This revelation was quite surprising but was traced back to the burner liner which was not centered in the burner. This latter fact caused the inlet air to be unevenly distributed about the burning zone, and shifted the hot portion of the flame off center. All other temperature readings in this report were taken in the hottest portion of the exhaust gas stream.

It is to be noted that the total temperature in figure (2) drops off sharply at d = 2.4"which as seen on figure (1) is the position of the last major shock. This is typical of all experimental runs using kerosene, and indicates the influence of shocks on total temperature increases. Comparing the amount of temperature increase to the strength of the shocks in figures (1) and (2), a definite relationship between the two is indicated.

Experimental results indicate that the attempt to obtain complete combustion was successful. The gas stream for both

the combustion of kerosene and hydrogen was not visible
except in a darkened room. Under the latter conditions the
kerosene exhaust was characterized by a bright yellow color.
The regions of high pressure, thât is the shock diamonds,
were distinctly outlined as the brightness was more intense.
Five to seven shock diamonds were distinctly visible. The
hydrogen exhaust however, was identified by a pale blue stream.
The shock diamonds were barely visible, the color being a
slightly deeper blue. The insertion of the thermocouple in
the exhaust stream, under the darkened condition above, did
not affect the color of the flame for either hydrogen or
kerosene. If the combustion of the original hydrocarbons was
taking place, the insertion of the thermocouple would most
certainly accentuate the combustion in the immediate region
and affect the color of the flame.

It was observed on all runs with kerosene, in which
total temperature traverses were taken out to a distance of
4.0" from the orifice, that a sharp break occurred in the
temperature curve in the interval between 2.5" and 3.0". It
is believed that the existence of incomplete combustion in
the gas stream would result in a more gradual decrease of
total temperature. Throughout all runs, thermocouple readings
indicated a temperature drop in the burner extension.

Under conditions of high pressure ratio, that is high
burner pressure, the combustion would tend to become more
complete. However, this condition in general, resulted in
a greater total temperature increase in the shock diamonds.

However, it is realized that the above results are not

positive proof of complete burning, but only tend to confirm
the attempts to complete combustion insofar as possible. It
is thought that the affects of incomplete combustion in the
gas stream, if at all present, are slight and may be neglected.

Figure (3) compares the gas stream total temperature
resulting from the combustion of kerosene and of hydrogen.
The kerosene curve is typical of many runs, exhibiting the
total temperature increase in the shock diamonds. However,
the hydrogen curve is almost flat, the variations are negligible,
being no larger than the normal potentiometer fluxuations en-
countered. Figure (4) is the comparison of the same fuels
at a different burner temperature. It is seen that the same
result occurs. In both of the above comparisons, the same
pressure ratio of 2.9 was used. Figure (5) shows the static
pressure traverse for the kerosene run and figure (6) shows
the total pressure traverse for the hydrogen run. These
traverses verify the fact that shock diamonds were being formed
during these particular runs. Bailey's experiments verify
the above results. He burned a mixture of hydrogen and air,
and observed no temperature increases in the shock diamonds.

These results indicate that the type of fuel undoubtedly
plays a major part in total temperature increase in shock
diamonds. Of course, the major difference in the above fuels
is that kerosene contains carbon and hydrogen does not. Thus
the discrepancy can be very well explained by the theory of
the after burning of carbon monoxide. The decrease in total
temperature before the shock diamond is encountered, as shown
in figure (3) for kerosene, is typical of all runs with this

fuel. As outlined previously, recombination of carbon monoxide and oxygen will be accentuated in regions of high pressure and decreased in regions of low pressure. Since the pressure drops as the velocity increases approaching the first shock, this theory would predict a drop in total temperature. Since the pressure is increased in the diamond, one should expect a total temperature rise. A minor contribution to the above decrease in temperature is the cooling affect on the thermocouple when in high velocity flow. In fact, the slight variation of the hydrogen curves may be a result of this cooling affect. The re-occurrence of this temperature rise in each succeeding shock can be explained by the fact that the successive dissociation and recombination of the molecules will prolong the combustion process. It is also possible that the violent accelerations and decelerations aid in the above dissociations. It has been shown in figures (1) and (2) that the greater the intensity of the shock the greater the temperature rise. This result is expected as the greater the pressure, the more carbon monoxide and oxygen will combine and thus a higher total temperature.

Temperature increases of 100 to 150 degrees in shock diamonds have been observed in previous reports (1) (2), at pressure ratio of three, where as experiments contained in this report show a smaller increase of 45 to 75 degrees. However, since the presence of impurities or moisture greatly reduces the abnormal dissociation of the carbon dioxide, this variation is to be expected. It is entirely possible that the kerosene and inlet air used in previous experiments

contained less impurities and moisture. Also the burner

temperatures in above reports were in the vicinity of 2400

to 3000°R which would increase considerably the degree of

dissociation.

In figures (3) and (4), referring to the kerosene runs,

the temperature of the gas stream at the orifice is 1024°F for

a burner temperature of 1002°F and is 1632°F for a burner

temperature of 1450°F. The hydrogen curves, although below

the burner temperature are seen to approach the latter as

burner temperature is increased from 1002°F to 1450°F. The

explanation of this is not readily apparent. It appears

to be a result of incomplete combustion but experimental re-

sults have shown the combustion to be very nearly complete

if not entirely complete. After burning could hardly explain

it, as there appears to be more after burning for the burner

temperature of 1002°F than for the run at 1450°F., as shown

by the relative temperature increase in the shock diamond.

Hydrogen exhibits the same tendency which is even more diffi-

cult to connect with incomplete combustion and after burning.

It would seem more plausible that the burner temperature is

incorrect. It has been shown that the hottest portion of the

flame varied in the gas stream. It is then logical that it

will also vary in the burner. Since the thermocouples in

the burner were fixed in the center of the burner, it is

possible that the recorded temperature was low. Bailey re-

ported instances of the gas stream temperature being up to

1000 degrees greater than burner temperature. Burner tem-

peratures in these experiments were calculated from accurate

heat balances, however no thermocouple readings were taken in the burner to verify the heat balance results. Assuming the burner temperatures were correct, this phenomenon defies all present day theories.

Potentiometer fluxuations in the gas stream were of larger magnitude when burning kerosene, than when burning hydrogen. However, the burner temperature fluxuations were small and of the same magnitude for both kerosene and hydrogen. This could indicate that some form of activity is occurring in the kerosene exhaust stream, conforming to the after burning theory.

It has been mentioned that the kerosene exhaust stream was characterized by a bright yellow glow, the intensity of which was much greater in the shock diamonds. That this could well be the after burning of carbon monoxide has been definitely indicated by the experiments of Withrow and Rossweiler. [3] They used a stroboscopic method which enabled them to study the spectrum of the light emitted from the combustion chamber of an internal combustion engine, at any stage during the charge. Ordinary photographs revealed that there was a marked re-illumination of the gases through which the flame had passed, this occurring during the pressure rise, accompanying the rapid burning of the last part of the charge. Spectrographs were taken of the flame front and of this so-called after glow. The after glow of all the organic fuels studied showed only the carbon monoxide flame spectrum and the OH bands. The CH and C2 bands which characterized the flame front were not present in the after glow. This indicates that the light emitted after the flame has

passed through the charge is not due to oxidation of the original hydrocarbons.

The above after glow is analagous to that found in kerosene exhaust gases, the regions of high pressure accentuating the combustion of carbon monoxide and oxygen, resulting in a more pronounced after glow.

The exhaust gases of the hydrogen exhibited no after glow which is, of course, predicted by the carbon monoxide theory. The slightly deeper blue color in the shock diamonds can readily be explained. Since the pressure in the shock diamonds is greater than that in the surrounding vicinity, the density is also greater, thus a greater degree of radiation.

It is of interest to note that Bailey reported the high pressure shock diamonds were usually visible, but instances occurred, under apparently the same conditions, when the diamonds were not visible or barely so. This would indicate a hidden variable, most likely concerned with the composition of the combustion mixture. This can be explained by the carbon monoxide theory. It has been shown that moisture and impurities exert a great influence, and a large decrease in the amount of after burning. Therefore, any appreciable change in the physical properties of the combustion mixture could account for the disappearance of the visible shock diamonds.

Table I contains a compulation of the results obtained with various pressure ratios and burner temperatures. In general it is seen that greater pressure ratios result in

greater temperature increases, as indicated by figure (7).
The latter is true for burner temperature from 800 - 1450°F.
It is seen at lower burner temperature, pressure ratio appears
to have little or no effect, the magnitude of temperature
increases is approaching the potentiometer fluxuation.

At higher pressure ratios the total temperature increase
is expected to be greater than for lower pressure ratios in
accordance with the carbon monoxide theory. Since the ab-
normal dissociation would be greater at higher temperature,
the theory predicts greater temperature increases for higher
burner temperature. No attempt has been made to verify the
latter statement due to insufficient experimental results.
However, figure 7 indicates a tend in the right direction.
The spread of points seen in figure 7 could be the result
of two factors, the burner temperature variation, and the
possibility of varying physical and chemical properties of
the combustion mixture.

Comparing figures 2 and 2A, it is seen that for the
latter the total temperature at the orifice is lower than
for the former, both at the same burner temperature. Since
the burner pressure is much less for a pressure ratio of 1.64,
the rate of recombination of carbon monoxide and oxygen is
less, resulting in lower total temperature.

The results of this report throw very little light on
the theory of ionization. Since it is known that hydro-
carbon fuels are more likely to ionize than are hydrogen
fuels, ionization could possibly play a part in the observed
results. Due to lack of fundamental knowledge of ionization
in a high velocity gas stream, the theory seems to be neither

proved or disproved. It is felt that ionization could
at least play a minor role in producing total temperature
increase in shock diamonds. However, until more direct
evidence is available, this can only be a speculation.

The lack of equipartition of energy theory appears
to break down because of two considerations. First, it seems
more logical that a shock would tend to place the molecule
further from equilibrium, thus lower the translational
energy and the total temperature. The second, which is
more convincing involves the relaxation time of a molecule.
The relaxation time is defined as the time interval required
for the conversion of vibrational energy into thermal or
translational energy. In other words, the time for a mole-
cule to reach equilibrium. The actual time has been cal-
culated; it will of course vary for different molecules
and for the conditions which exist. However, it is fairly
well agreed upon that the required time lies between 10^{-8}
and 10^{-13} seconds. It can be shown that the time required
for a molecule to reach the first shock is of the order of
2×10^{-5} secs. The latter is based on experimental results,
which indicate that a distance of .5" is required before
the appearance of the first diamond. The mach number used
in the calculations was that of the stream just before hitting
the shock, thus its greatest value. It is apparent that
2×10^{-5} seconds is the shortest possible time, the actual
time no doubt being of greater duration. However, using
this figure, it is readily seen that the molecule will al-
ready be in equilibrium before it reaches the shock diamond.

Thus any increase in translational energy and therefore total temperature should have occurred before reaching the shock.

In conclusion it may be said that the after burning of carbon monoxide is the most likely of the presented theories which can explain the increased total temperature found to exist in shock diamonds. In view of the meager experimental evidence conducted in this field to date, it must be admitted that ionization and after burning are still possibilities. In fact, the influence of the above three theories could well be combined to produce the observed phenomenon.

CONCLUSIONS

When a gas flows through an orifice under a pressure ratio greater than that needed to produce sonic velocity, the sudden adjustment of the gas pressure to the lower back pressure produces a variety of angle shock patterns. When these shock patterns occur in high temperature products of kerosene-air combustion, total temperature increases in the regions of high pressure, e.g. behind the shock wave. When these shock patterns exist in high temperature products of hydrogen-air combustion, total temperature does not increase.

These results indicate that the after burning of carbon monoxide is the most plausible explanation of the shock diamond phenomenon and that further investigation of this theory should definitely be conducted. Incomplete combustion and ionization are possible but not probable causes.

RECOMMENDATIONS

1. Conduct an investigation to determine the spectro
    character of the region within the shock diamond.
    Thus it could be definitely determined if the in-
    creased total temperature is due to after burning
    of carbon monoxide or combustion of original hydro-
    carbons.

2. Conduct an investigation to determine the degree
    of ionization in a high velocity exhaust gas
    stream containing shock diamonds.

3. Conduct an investigation into the problem of gas
    stream temperature measurements which are of
    greater value than the burner temperature. An
    accurate method of determining burner temperature
    would be a necessary requisite.

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TABLE NO. 1

TOTAL AND STATIC PRESSURE TRAVERSE

DATA FOR FIGURE NO. 1

Distance from Orifice in Inches	P4 Gage	P4 Correction Factor	P4 ABS.	Po4 Gage	Po4 ABS.
0	41.5	≠30.3	71.80	57.2	87.6
.1	25.15	≠30.3	55.45	56.7	87.1
.2	11.4	≠ 2.2	32.57	56.8	87.2
.3	8.9	- .6	29.7	52.6	83.0
.4	6.9	- 4.6	25.7	49.3	79.7
.5	6.1	- 6.2	24.1	48.9	79.3
.6	12.5	≠ 6.6	36.9	52.1	82.5
.7	13.1	≠ 7.8	38.1	55.5	85.9
.8	12.45	≠ 6.5	36.8	56.3	86.7
.9	9.55	≠ 0.7	31.0	55.1	85.5
1.0	6.35	- 5.7	24.6	50.3	80.7
1.1	9.2	0	30.3	50.1	80.5
1.2	14.6	≠10.8	41.1	52.1	82.5
1.3	13.5	≠ 8.6	38.9	55.1	82.5
1.4	8.95	- 0.5	29.8	55.8	86.2
1.5	7.7	- 3.0	27.3	54.5	84.9
1.6	6.2	- 6.0	24.3	51.2	81.6
1.7	9.05	- 0.3	30.0	51.2	81.6
1.8	13.95	≠ 9.5	39.8	53.0	83.4
1.9	10.4	≠ 2.4	32.7	55.0	85.4
2.0	7.6	- 3.2	27.1	54.5	84.9
2.1	7.3	- 3.8	26.5	53.7	84.1
2.2	7.0	- 4.4	25.9	51.7	82.1
2.3	8.2	- 2.0	28.3	52.5	82.9
2.4	9.9	≠ 1.4	31.7	52.5	82.9
2.5	7.8	- 2.8	27.5	49.9	80.3
2.6	7.7	- 3.0	27.3	49.2	79.6
2.7	8.15	- 2.1	28.2	50.2	80.6
2.8	7.9	- 2.6	27.7	50.4	80.8
2.9	8.0	- 2.4	27.9	47.4	77.8
3.0	8.0	- 2.4	27.9	45.2	75.6
3.1	8.2	- 2.0	28.3	43.5	73.9
3.2	9.4	≠ 0.4	30.7	42.7	73.1
3.3	9.45	≠ 0.5	30.8	42.5	72.9
3.4	9.3	≠ 0.2	30.5	41.0	71.4
3.5	9.2	0	30.3	40.3	70.7
3.6	9.4	≠ .4	30.7	38.7	69.1
3.7	9.5	≠ .6	30.9	36.9	67.3
3.8	9.5	≠ .6	30.9	35.4	65.8
3.9	9.5	≠ .6	30.9	35.2	65.6
4.0	9.45	≠ .5	30.8	34.0	64.4

P1 = 60" Hg. gage   Pa = 30.4" Hg.   P3/Pa = 2.85
P12 = 2.95" Hg.   Orifice = .6"   To2 = 913° F
P23 = 1.10" Hg.   Fuel = Kerosene   To3 = 780° F
P4 Correction Factor = -9.2 (See Sample Calculations)

TABLE NO. 2

TOTAL TEMPERATURE TRAVERSE

DATA FOR FIGURE 2

Dist. From Orifice in Inches	To2 M.V.	To2 oF	To3 M.V.	To3 oF	To4 M.V.	To4 oF
0	21.1	952	17.2	787	15.3	705
.1			17.1	782	15.1	697
.2			"	"	15.2	701
.3			"	"	15.0	692
.4			"	"	15.8	727
.5			"	"	16.0	735
.6			"	"	16.0	735
.7			"	"	16.1	740
.8			"	"	15.8	727
.9			"	"	15.5	714
1.0	21.2	956	17.3	790	16.1	740
1.1			"	"	16.4	752
1.2			"	"	16.3	748
1.3			"	"	16.7	765
1.4			"	"	16.4	752
1.5			"	"	16.2	744
1.6			17.4	795	17.0	778
1.7			17.3	790	17.2	787
1.8			17.4	795	17.3	791
1.9			"	"	17.2	787
2.0	21.3	960	"	"	16.8	769
2.1			"	"	16.6	761
2.2			"	"	16.0	735
2.3			"	"	16.0	735
2.4			"	"	16.3	748
2.5			"	"	16.1	740
2.6			"	"	14.9	688
2.7			17.3	790	14.2	659
2.8			"	"	14.1	655
2.9			"	"	13.8	641
3.0	21.2	956	"	"	13.2	615
3.1			"	"	12.7	594
3.2			17.4	795	12.3	576
3.3			17.3	790	12.1	567
3.4			17.3	790	11.8	555
3.5			17.4	795	11.5	542
3.6			17.3	790	10.9	515

P1 = 60" Hg. gage   Pa = 30.37" Hg.

P12 = 2.90" Hg.   Orifice = .6"

P23 = 1.10" Hg.   Fuel = Kerosene

P3/Pa = 2.85

TABLE 2A

TOTAL TEMPERATURE TRAVERSE

DATA FOR FIGURE 2A

Distance From Orifice in Inches	To2 M.V.	To2 °F	To3 M.V.	To3 °F	To4 M.V.	To4 °F
0	20.4	922	17.0	778	13.7	636
.1	"	"		"	13.7	636
.2	"	"		"	13.8	641
.3	"	"		"	14.0	650
.4	"	"		"	14.0	650
.5	"	"		"	14.1	654
.6	"	"		"	14.2	658
.7	"	"		"	14.2	658
.8	"	"		"	14.5	671
.9	"	"		"	14.6	675
1.0	"	"		"	14.6	675
1.1	"	"		"	14.6	675
1.2	"	"		"	14.6	675
1.3	"	"		"	14.5	671
1.4	"	"		"	14.6	675
1.5	"	"		"	14.7	680
1.6	"	"		"	14.9	688
1.7	"	"		"	14.9	688
1.8	"	"		"	14.9	688
1.9	"	"		"	15.0	692
2.0	"	"		"	14.9	688
2.1	"	"		"	15.0	692
2.2	"	"		"	15.0	692
2.3	"	"		"	14.9	688
2.4	"	"		"	14.9	688
2.5	"	"		"	14.9	688
2.6	"	"		"	14.9	688
2.7	"	"		"	14.8	684
2.8	"	"		"	14.7	680
2.9	"	"		"	14.6	675
3.0	"	"		"	14.2	658
3.1	"	"		"	14.1	654
3.2	"	"		"		
3.3	"	"		"	13.9	645
3.4	"	"		"		
3.5	"	"		"	13.0	607
3.6	"	"		"		
3.7	"	"		"	12.5	585

P1 = 25."0 Hg gage   P3/Pa = 1.64

P12 = 3.9" Hg   Orifice = .7"

P23 = 1.5" Hg   Fuel = Kerosene

Pa = 30.35" Hg.

TABLE No. 3

TOTAL TEMPERATURE TRAVERSE

DATA FOR FIGURE No. 3

Distance From Orifice in Inches	To2 M.V.	To2 °F	To3 M.V.	To3 °F	To4 M.V.	To4 °F
0	24.2	1082	22.3	1002	22.8	1024
.1	"	"	"	"	22.7	1019
.2	"	"	"	"	22.4	1006
.3	"	"	"	"	22.6	1015
.4	"	"	"	"	23.4	1049
.5	"	"	"	"	23.4	1049
.6	"	"	"	"	23.1	1036
.7	"	"	"	"	22.9	1029
.8	"	"	"	"	23.4	1049
.9	"	"	"	"	23.4	1049
1.0	"	"	"	"	23.3	1044

Pl = 59.0" Hg. gage   Pa = 30.10" Hg.
Pl2 = 0.5" Hg.   Orifice = .4"
P23 = 0.35" Hg.   Fuel = Kerosene
P3/Pa = 2.93

Distance	To2 M.V.	To2 °F	To3 M.V.	To3 °F	To4 M.V.	To4 °F
0	25.2	1125	22.0	990	20.2	913
.1	"	"	"	"	20.1	910
.2	"	"	"	"	20.2	913
.3	"	"	"	"	20.2	913
.4	"	"	"	"	20.2	913
.5	"	"	"	"	20.1	910
.6	"-	"	"	"	20.1	910
.7	"	"	"	"	20.2	913
.8	"	"	"	"	20.1	910
.9	"	"	"	"	20.0	905
1.0	"	"	"	"	19.9	900

Pl = 59.5" Hg. gage   P3/Pa = 2.98
Pl2 = .35" Hg.   Orifice = .4"
P23 = .40" Hg.   Fuel = Hydrogen
Pa = 29.58

TABLE NO. 4

TOTAL TEMPERATURE TRAVERSE

DATA FOR FIGURE NO. 4

Distance From Orifice in Inches	To2 M.V.	To2 °F	To3 M.V.	To3 °F	To4 M.V.	To4 °F
0	37.5	1660	32.8	1450	36.9	1631
.1	"	"	"	"	36.9	1631
.2	"	"	"	"	36.9	1631
.3	"	"	"	"	37.0	1635
.4	"	"	"	"	37.3	1650
.5	"	"	"	"	37.5	1659
.6	"	"	"	"	37.2	1645
.7	"	"	"	"	37.3	1650
.8	"	"	"	"	37.5	1659
.9	"	"	"	"	37.3	1650
1.0	"	"	"	"	37.3	1650

$P1 = 59.0''$ Hg. gage $P3/Pa = 2.93$
$P12 = 0.4''$ Hg.   Orifice $= .4''$
$P23 = 0.3''$ Hg.   Fuel = Kerosene
$Pa = 30.10''$ Hg.

Distance	To2 M.V.	To2 °F	To3 M.V.	To3 °F	To4 M.V.	To4 °F
0	37.0	1635	33.0	1460	32.8	1450
.1	"	"	"	"	32.7	1445
.2	"	"	"	"	32.7	1445
.3	"	"	"	"	32.7	1445
.4	"	"	"	"	32.8	1450
.5	"	"	"	"	32.8	1450
.6	"	"	"	"	32.6	1442
.7	"	"	"	"	32.4	1433
.8	"	"	"	"	32.3	1428
.9	"	"	"	"	32.0	1415
1.0	"	"	"	"	31.7	1402

$P1 = 59.5''$ Hg gage $P3/Pa = 2.99$
$P12 = .4''$ Hg.   Orifice $= .4''$
$P23 = .15''$ Hg.   Fuel = Hydrogen
$Pa = 29.58$

TABLE NO. 5

STATIC PRESSURE TRAVERSE

DATA FOR FIGURE NO. 5

Distance From Orifice in Inches	P4 Gage	P4 Correction Factor	P4 ABS
0	49.9	≯ 30.1	80.0
.1	33.9	≯ 30.1	64.0
.2	13.5	≯ 8.8	38.9
.3	4.25	− 9.7	20.4
.4	6.05	− 6.0	24.1
.5	6.30	− 5.6	24.5
.6	14.70	≯ 11.2	41.3
.7	8.70	− 0.8	29.3
.8	5.10	− 8.0	22.1
.9	11.90	≯ 5.6	35.7
1.0	9.95	≯ 1.7	31.8

P_1 = 59" Hg. gage   P4 Correction Factor = − 9.1" Hg
P_{12} = 0.4" Hg P_3/P_a = 2.93 T_{o2} = 1660° F
P_{23} = 0.3" Hg   Orifice = .4" T_{o3} = 1450° F
P_a = 30.1" Hg   Fuel = Kerosene

TABLE NO. 6
TOTAL PRESSURE TRAVERSE
DATA FOR FIGURE NO. 6

Distance From Orifice in Inches	Po4 Gage	Po4 ABS
0	> 60.	−
.1	> 60.	−
.2	> 60.	−
.3	54.4	84.0
.4	47.1	76.7
.5	51.8	81.4
.6	57.7	87.3
.7	57.8	87.4
.8	50.7	80.3
.9	51.2	80.8
1.0	55.1	84.7

P_1 = 59.5" Hg gage P_3/P_a = 2.99 T_{o2} = 1645° F
P_{12} = .3" Hg   Orifice = .4" T_{o3} = 1460° F
P_{23} = .4" Hg   Fuel = Hydrogen
P_a = 29.58

TOTAL TEMPERATURE VARIATION

TABLE NO. 7

KEROSENE

Press.Ratio P_3/P_a	To B.S. oF	To A.S. oF	$\triangle$ To	To Burner oF	Orifice Dia. (Inches)
3.0	1540	1595	55	1330	.4
2.93	1105	1150	45	1000	.4
2.93	1630	1660	30	1450	.4
2.91	860	925	65	1080	.6
2.85	700	740	40	790	.6
2.71	1025	1100	75	1085	.6
2.69	714	748	34	790	.6
2.69	676	700	24	--	.7
2.56	905	950	45	1000	.6
2.53	714	748	34	790	.6
2.51	790	816	26	--	.7
2.40	975	1010	35	1070	.6
2.38	714	740	26	790	.6
2.30	1285	1310	25	1330	.4
2.23	906	914	8	--	.7
2.22	714	736	22	790	.6
2.85	240	249	9	323	.6
2.85	187	200	13	250	.6
2.79	279	289	10	296	.6
2.17	204	208	4	250	.7
2.13	292	293	1	296	.6

To B.S. = total temperature just before first shock.

To A.S. = total temperature just after first shock.

$\triangle$ To = To A.S. - To B.S.

SAMPLE CALCULATIONS

A. Calculation of time required for a molecule
   to travel from orifice to first shock diamond:

   1. Mach number of stream just before first shock.

$Po3 = 60 - 4.05 / 30.4 = 86.35''$ Hg abs.
$P4$ (Just before first shock) $= 22''$ Hg abs.

$Po3/P_4 = 3.92$

$$M_4 = \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P_{o1}}{P_4}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$ Assume Reversibility (26)

$$M_4 = \sqrt{5.55\left[1.436 - 1\right]}$$ Assume $\gamma = 1.36$

$$\therefore M_4 = 1.55$$

   2. Calculation of time required using max.value

of $M4 = 1.55$ $To4 = 740 / 460 = 1200°R$

$$M_4 = f\left[\frac{V_4}{\sqrt{\gamma g R T_{o4}}}\right] = 1.275$$ FROM REF (26)

$$V_4 = 1.275\sqrt{1.36 \times 32.2 \times 53.4 \times 1200}$$

$$V_4 = 1.275\sqrt{2,800,000} = 2130 \, FT/SEC.$$

$$V_4 = 25,600 \, INCHES/SEC.$$

From Fig. (2) distance $= .5$ in.

$$\therefore t = \frac{distance}{velocity} = \frac{.5 \, in.}{25,600 \, in/sec} = \underline{\underline{1.95 \times 10^{-5}}} \, SEC.$$

B. Since the values of P_4 fell below atmospheric

pressure it was necessary to convert the

conventional straight 60" Hg. gage manometer

into a modified U tube as shown.

TO PITOT TUBE

30.0"   12.0" 9.2" 5.0"
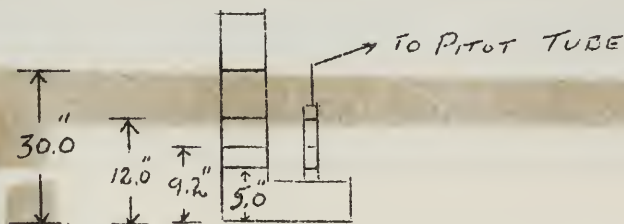
1. Calculations necessary to correct manometer

readings.

case (a): -

P_4 (gage, uncorrected) = 5.0" Hg.   Pa = 30.0"Hg.
            9.2" Hg. = Correction factor

2 (9.2 - 5.0) = 2 x 4.2 = 8.4
8.4" Hg. is the actual amount which the at-
mospheric pressure is greater.

∴ P_4 (absolute, corrected) = 30.0 -8.4 = 21.6"Hg

case (b): -
P_4 (gage, uncorrected) = 12.0" Hg.
2 (12 - 9.2) = 5.6" Hg.
∴ P_4 (absolute, corrected) = 30.0 ≠ 5.6 = 35.6" Hg.

Case (c): -
P_4 (gage, uncorrected) = 30.0" Hg.
P_4 (absolute, corrected) = 30.0 ≠ 30.0 = 60" Hg.

For any reading greater than 18.4, it is only

necessary to add the atmospheric pressure to obtain

P_4 absolute, corrected.
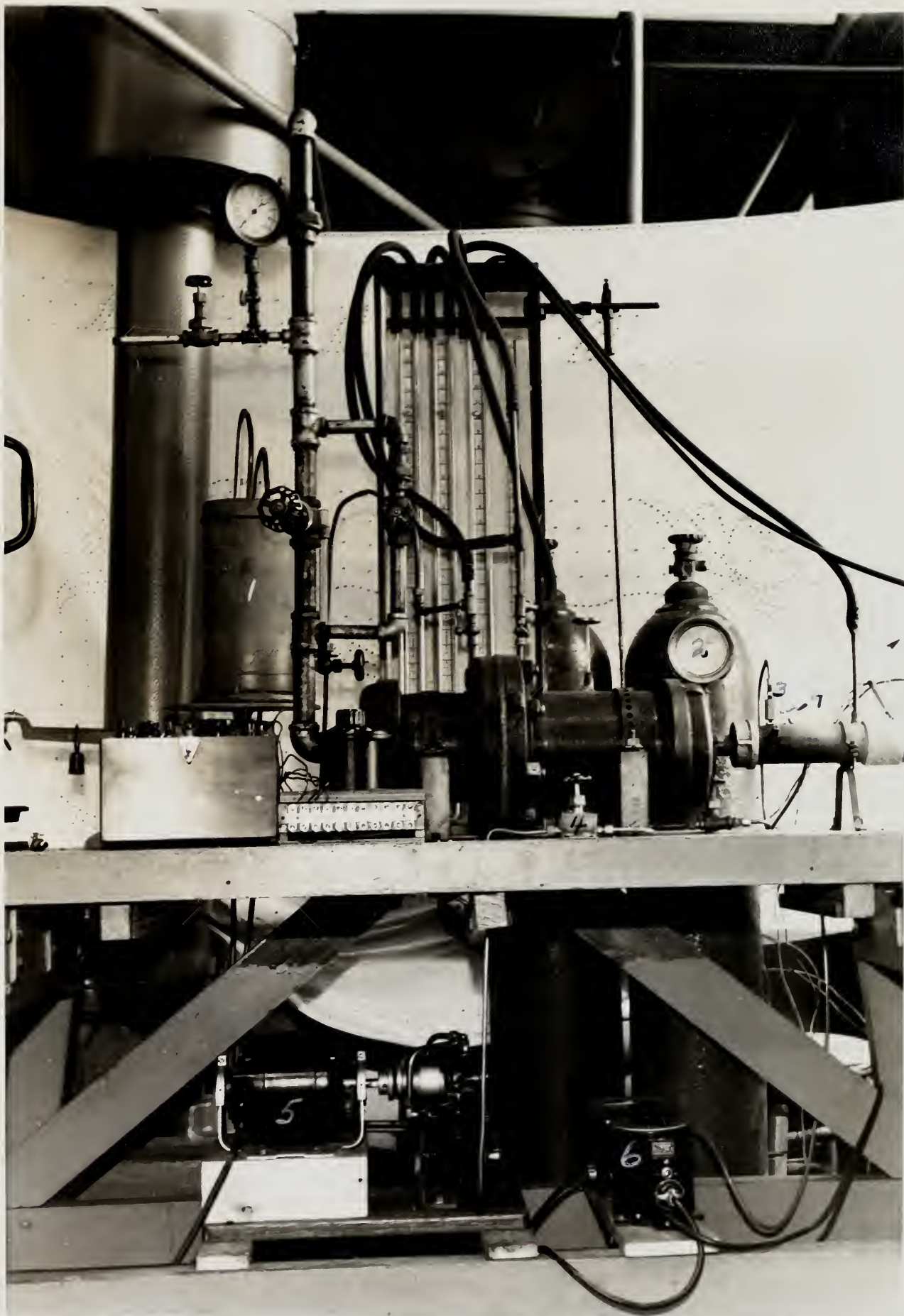
PLATE No. 1

Key to Plate 1

1. Fuel(kerosene) tank and scale.
2. Fuel gage.
3. Fuel inlet.
4. Fuel valve.
5. Fuel pump.
6. Power Stat, Voltage regulator.
7. Spark plug.

Key to Plate 2

1. Burner.
2. Burner extension.
3. Orifice cap.
4. Sliding plate arrangement.
5. Air metering device.
6. U tube manometer.
7. Potentiometer.
8. Pitot-static tube.
9. Thermocouple selector switch.
10. Bleed off valve.
11. Air supply.
12. Thermocouples -- burner extension.
13. Hydrogen supply.

PLATE No. 2
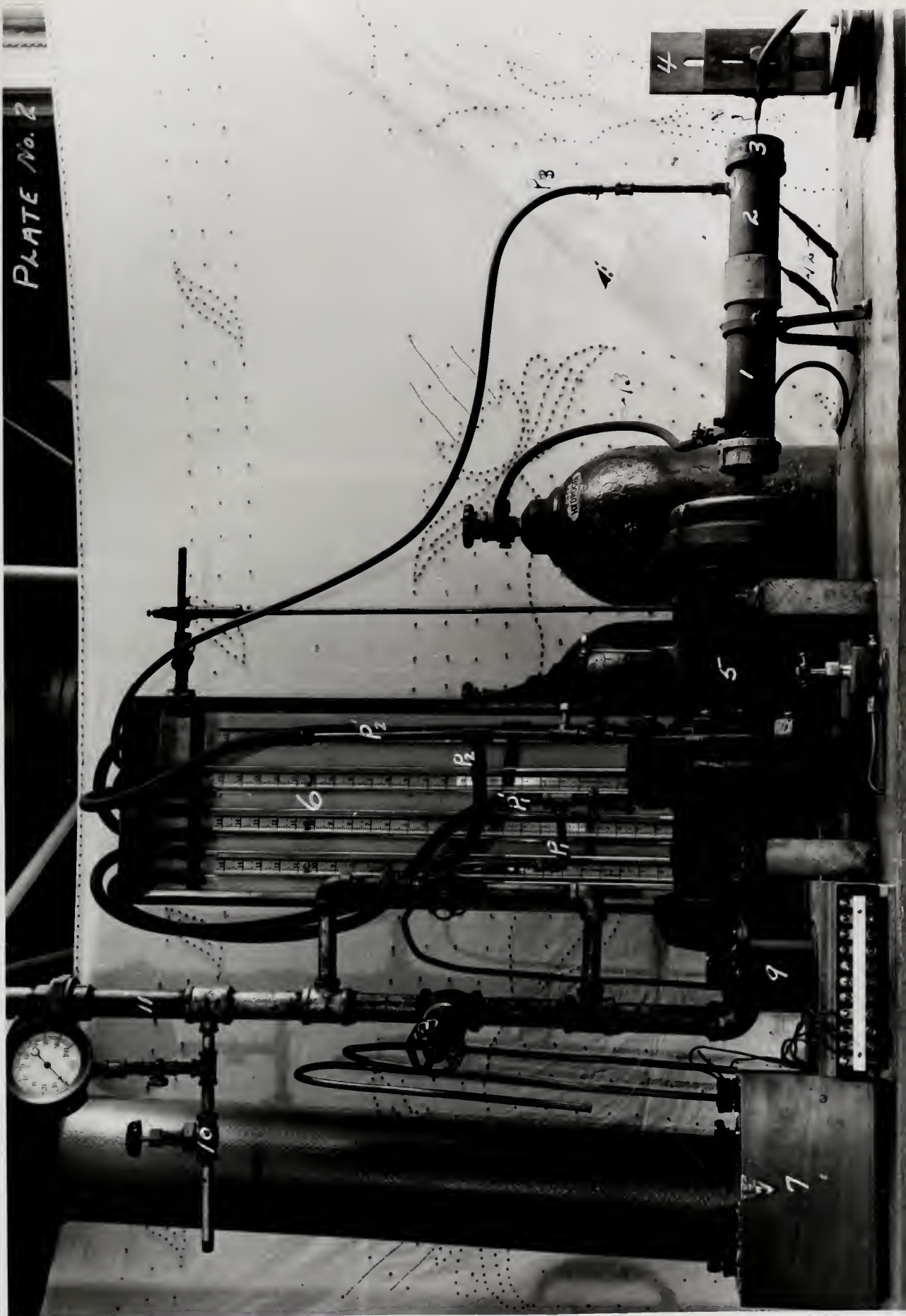
Key to Plate 3.

1. Burner liner.
2. Spark plug.
3. Hydrogen burner tip.
4. Kerosene burner tip.
5. Fitting to secure and center burner
   tip in burner.

Key to Plate 4

1. Pitot-static tube.
2. Pitot tube.
3. Thermocouple- stream.
4. .7" orifice.
5. .6"   "
6. .5"   "
7. .4"   "
8. Burner extension.
9. Burner.

Schematic Sketch of Burner Assembly
Plate No. V

FORWARD CURVED BLADE PRESSURE TRAVERSE
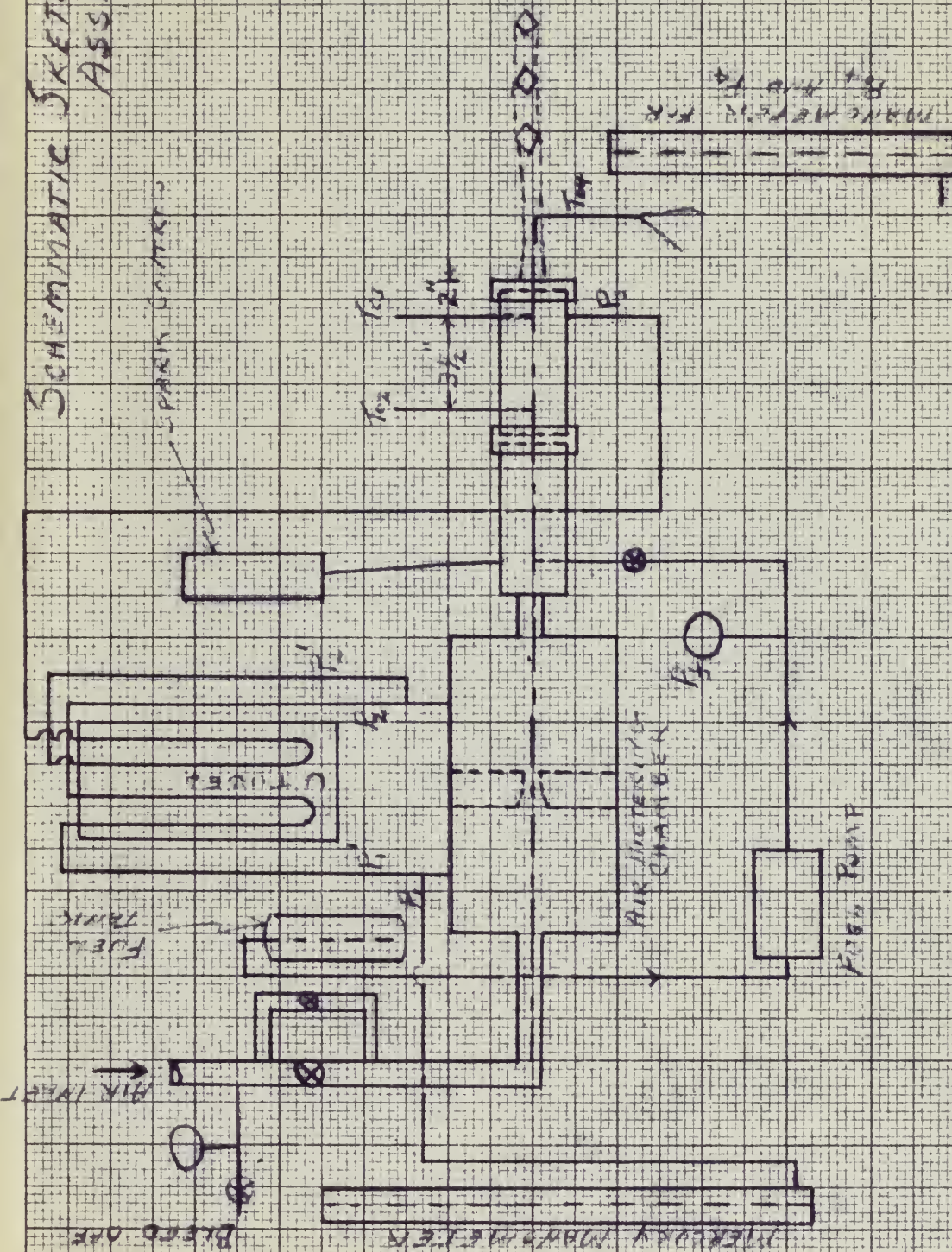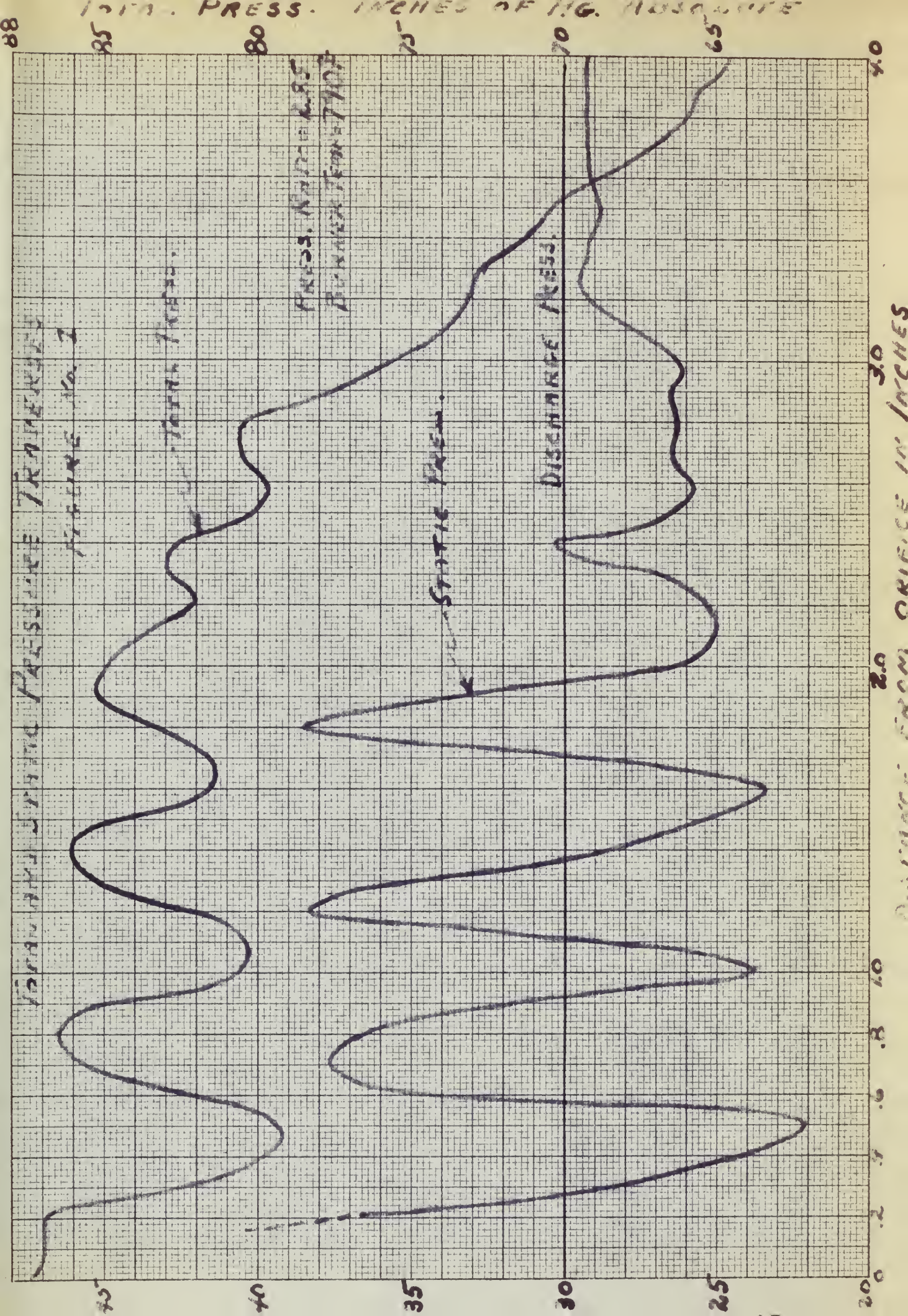
TOTAL TEMPERATURE TRAVERSE
Figure No. 2

Press. Ratio = 2.85
Burner Temp. = 790°F
Kerosene
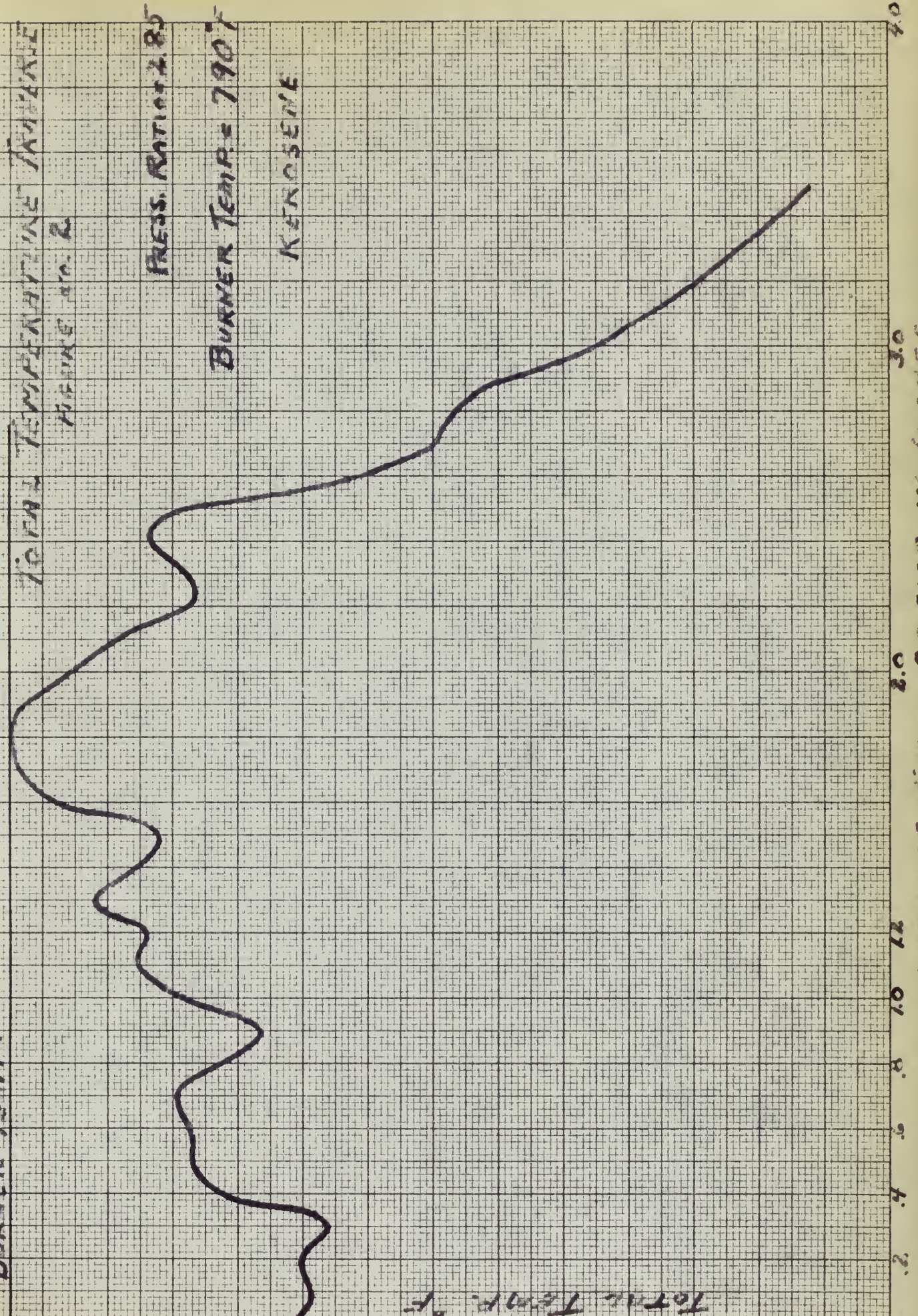
Distance from Orifice in Inches
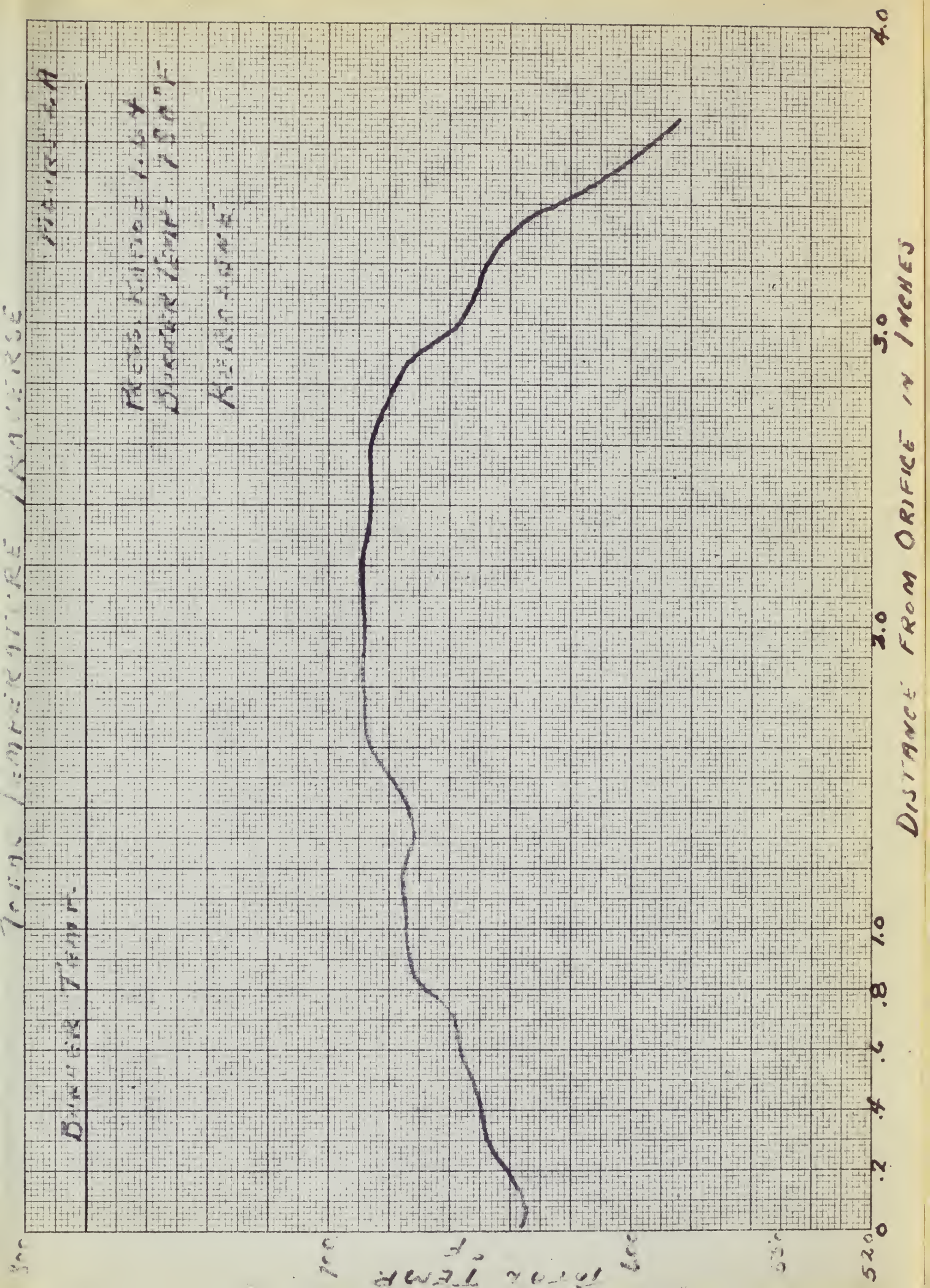
TOTAL TEMPERATURE TRAVERSE

FIGURE NO. 3

PRESS RATIO = 2.93

KEROSENE

BURNER FROM KEROSENE

BURNER TEMPERATURE

HYDROGEN

TOTAL TEMP. °F

0   .1   .2   .3   .4   .5   .6   .7   .8   .9   1.0

DISTANCE FROM ORIFICE IN INCHES

900   950   1000   1050

TOTAL TEMPERATURE TRAVERSE

FIGURE N°. 4

PRESS. RATIO 2.73

KEROSENE

BURNER EXIT TEMPERATURE

HYDROGEN

BLENDED STONE HYDROGEN
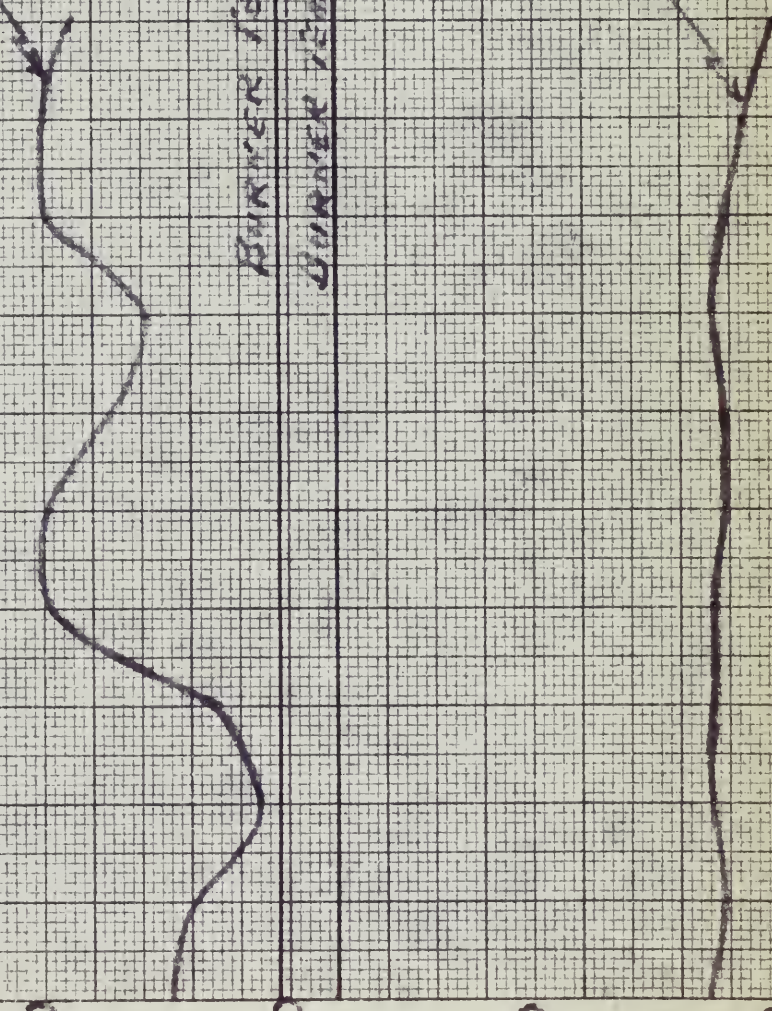
TOTAL TEMP. °F

1600

1500

1400

DISTANCE FROM ORIFICE IN INCHES

.1 .2 .3 .4 .5 .6 .7 .8 .9 1.0

STATIC PRESSURE TRAVERSE

FIGURE Nº 5

PRESS. RATIO= 2.93

BURNER TEMP.= 1450° F.

KEROSENE

DISCHARGE PRESS.
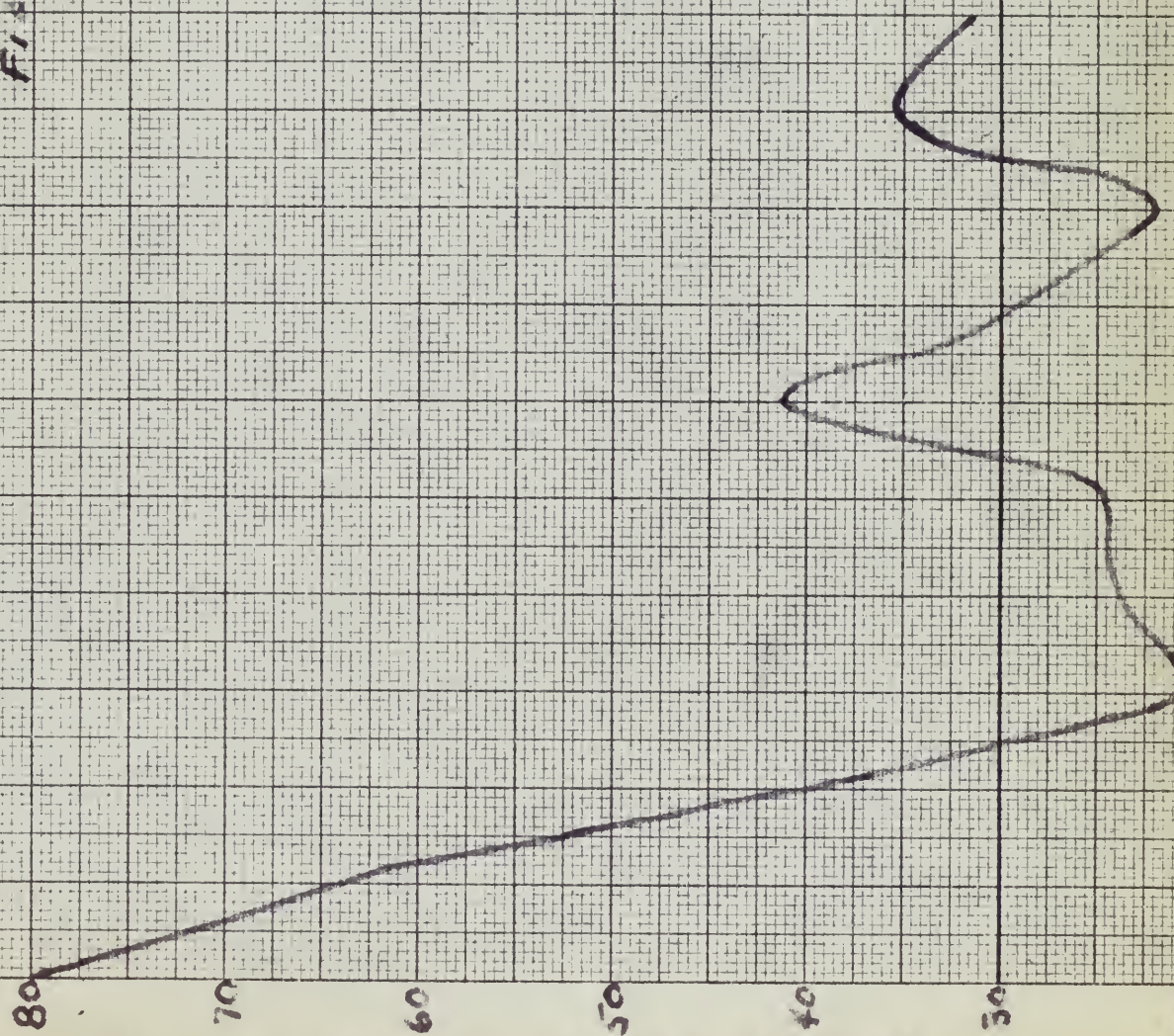
DISTANCE FROM ORIFICE IN INCHES

STATIC PRESS. INCHES OF HG. ABSOLUTE

TOTAL PRESSURE TRAVERSE
DOWNSTREAM

ATMOS. PRESS.: 29.51" Hg

PRESS. RATIO: 2.95

BURNER TEMP.: 1445° F

MEASURED

Monograph

TOTAL PRESS: INCHES OF HG. ABSOLUTE
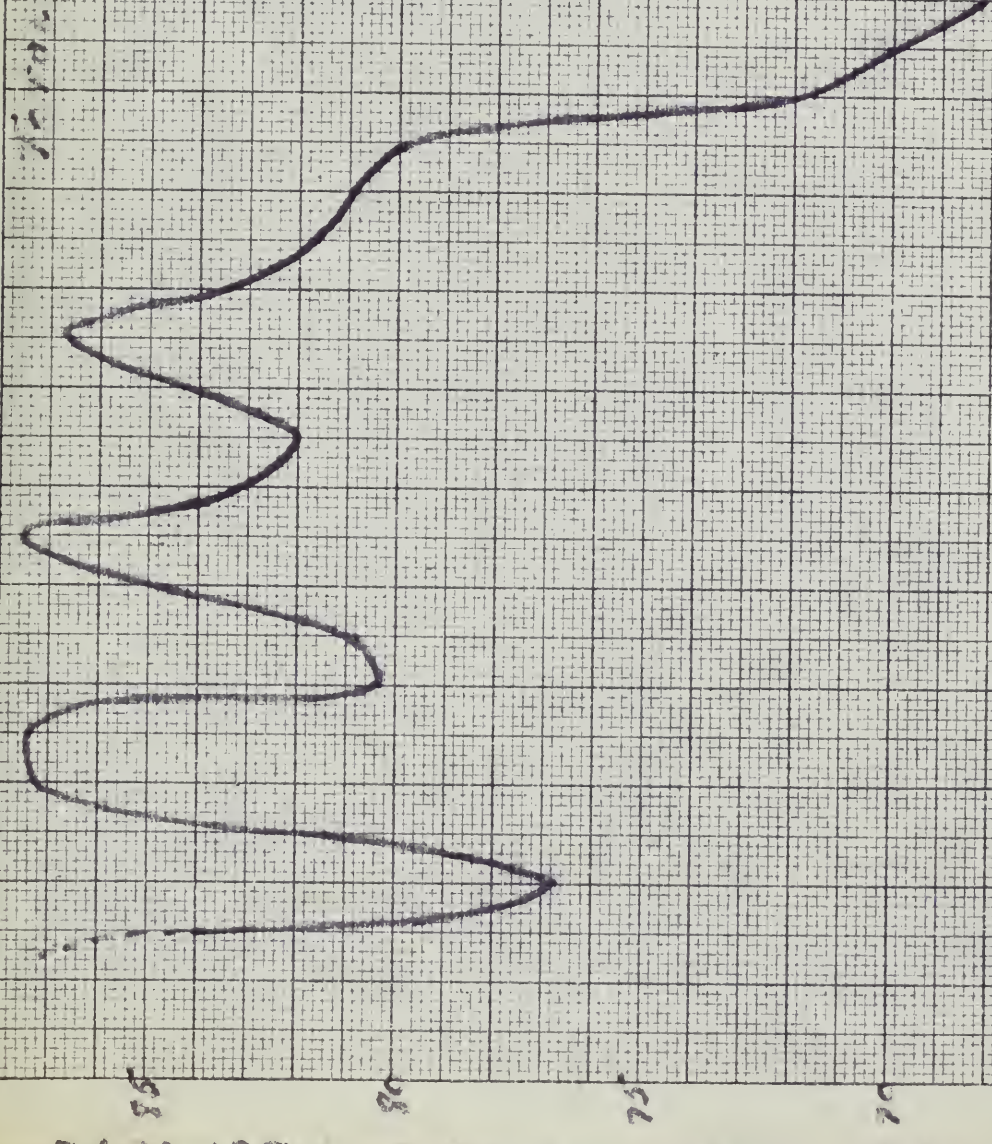
DISTANCE FROM ORIFICE IN INCHES

Total Temperature Increase Vs. Pressure Ratio
Figure No. 7

⊙ - - - Burner Temp = 900 to 1450 F
X - - - Burner Temp = 200 to 300 F

Kerosene

PRESSURE RATIO

Total Temp. Increase - ΔT₀

DATE DUE			